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It's Not Just the Light: Understanding the Factors Causing Situational Visual Impairments During Mobile Interaction

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ABSTRACT

Mobile technologies are used in increasingly diverse and challenging environments. With the predominantly visual nature of mobile devices, Situational Visual Impairments (SVIs) are a growing concern. However, fundamental knowledge is lacking about the causes of SVIs, how people deal with SVIs, and whether their solutions are effective. To address this, we first conducted a convenience-sampled online questionnaire with 174 participants, and identified many causes and (ineffective) solutions. To firmly ground our initial results, we then conducted a two-week ecological momentary assessment with 24 participants, balanced by age and gender across Australia and Scotland. We confirmed that SVIs are experienced often and during typical mobile tasks, and can be very frustrating. We identify a range of factors causing SVIs, discuss mobile design implications, and introduce an SVI Context Model rooted in empirical evidence. The contributions in this paper will support the development of new effective SVI solutions.

Author Keywords

Situational impairment; accessibility; mobile devices.

ACM Classification Keywords

H.5.m. Information Interfaces & Presentation: Miscellaneous

INTRODUCTION

Mobile devices are ubiquitous and go beyond only personal use. For example, tablets are used in classrooms [16], pilots are using iPads [56], dentists can enhance communication with patients [11], and mobile devices can provide medical professionals with educational and clinical support [3, 4, 34]. Mobile devices are recognised as useful tools in the workplace, but mobile devices need to be adaptable for different situations [1]. Safety concerns have led to investigations into the degree to which ambient light levels affect image quality on mobile displays, such as in medical settings [31, 61].

For years, the HCI and Accessibility fields have recognised the increased demands on device interaction caused by diverse contexts of use [38, 48, 57]. Mobile devices are used in many contexts, increasing the likelihood of experiencing situational impairments – a phenomenon in which the user finds a task difficult to complete that in another context they would have no issue with (e.g., typing a message while running versus standing still). Situational impairments can occur with non-digital devices but this is outside the scope of this research.

There have been studies identifying methods for evaluating mobile use in different contexts [6, 7], mechanisms proposed for adapting interaction according to context for improved accessibility and user experience [22, 23, 28], research investigating how mobile interaction changes in cold environments [42], and work to improve typing on touchscreen devices while walking [18]. However, we still have a lot to understand regarding mobile device situational impairments [43, 45].

Previous research does not explicitly gather information on what tasks people typically do when they experience SVIs, the consequences of SVIs as perceived by the user, and the diversity of other contributing factors to SVIs. Better solutions to mitigate SVIs can best be designed with a deeper understanding of the problem. Given the diversity of mobile device use contexts, we anticipate that the implications of SVIs range from annoyance to severe health and safety concerns.

For generality, we focus on the experience of typical mobile device users. To help understand the user context of SVIs, we conducted two studies. Study 1 used an online questionnaire to gather the experiences of 174 participants using a mobile device in bright environments. Study 2 used a two-week ecological momentary assessment with 24 participants across Australia and Scotland. In general, we looked to answer five broad research questions about SVIs: 1) How often are SVIs experienced? 2) In what contexts do SVIs occur? 3) What are the causes of SVIs? 4) How frustrating are SVIs? 5) What strategies are used to overcome SVIs?

We found that SVIs are experienced often, during a wide range of tasks, and can be very frustrating. In addition to ambient light, moving surroundings, physical obstacles, human accessories, position of device, device accessories, hardware design, software and system settings, content design, and cognitive and physiological factors also cause or exacerbate SVIs.

In this paper, we contribute novel data on mobile users' experiences of SVIs from a large online survey and a two-week ecological momentary assessment. We then discuss resulting design implications for mobile devices and present a new SVI

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Context Model for mobile devices. Our SVI Context Model can be used by different stakeholders (e.g., HCI and accessibility researchers, engineers, manufacturers, designers) to better understand the complexities of SVIs and account for SVIs.

RELATED WORK

Mobile computing allows for device interactions in many diverse situations compared to desktop computing, which often results in increased demands on the user. In addition to general use, mobile devices also need to be adaptable to different situations to function as successful tools within the workplace [1].

Early work by Newell [38] discussed impairments introduced by environmental factors and proposed *extra-ordinary HCI* to help conceptualise these challenging situations. Sears et al. [48] expanded this idea by emphasising that situational impairments arise from a context comprised of *Environment*, *Application*, and *Human* factors. Furthermore, Wobbrock [57] argued that it was time to begin improving mobile devices and create interfaces designed to reduce situational impairments.

Previous research has demonstrated similarities between the input errors from people with a motor impairment using a desktop compared to the errors made by people using small devices [59], as well as between the accessibility issues present for people with low vision and people using a mobile device [58]. Further research looking at situational impairments has investigated the challenge of walking and reading on a mobile phone [37], identified methods to evaluate mobile use in different contexts (e.g., while in motion [6, 7]), studied how mobile interaction changes in cold environments [42], proposed mechanisms that adapt interaction according to context for improved accessibility and user experience [22, 23, 28], and research has investigated improving typing on touchscreen devices and interaction while walking [18, 24]. Situational impairments can vary greatly for mobile device users [44], however, this research was limited by focusing on all situational impairments and a small sample size. There are also plans outlined to address severe situational impairments [45].

Recently, Sarsenbayeva et al. [43] published a systematic overview of known mobile device situational impairments. Out of seven situational impairments, there are four that require further investigation: "Ambient Light", "Ambient Noise", "Mood", and "Stress". Adaptive screen brightness was offered as a solution to ambient lighting situational impairments, and it was suggested that adaptive screen brightness may explain the limited research on situational impairments caused by ambient light. However, considering that not all situational impairments are created equally [44], adaptive screen brightness alone may not be sufficient.

In this paper, we focus on mobile device *situational visual impairments (SVIs)* – visual impairments arising from a mobile device user's context (e.g., the challenge of watching Netflix under bright sunlight) – since few studies explicitly explore the perspective of mobile device users experiencing SVIs.

Ambient light levels affect both people's visual perception and the clarity of displays. The eye goes through different stages of visual sensitivity as light increases: scotopic vision (in very low light) through to mesopic vision, and finally photopic vision (under high ambient light) in which full colour vision occurs [49]. Under both photopic and mesopic conditions, age can have a significant effect on reducing contrast sensitivity [40]. Most modern mobile devices have transmissive displays, which emit (as opposed to reflect) light [5], using either filtered backlighting or colour LEDs to produce an image. Due to the limited light production abilities of these displays, perceived image quality worsens as ambient light increases [25, 26, 30]. Other solutions for brighter displays have been introduced, such as Nokia's ClearBlack Display [14] and the One Glass Solution [20]. However, improved screen technologies are still susceptible to reduced brightness and contrast when viewed under bright ambient lighting [19, 31], and focusing on bright ambient lighting only addresses one cause for SVIs. Reducing screen brightness to conserve power creates a similar problem to viewing a screen in a bright environment.

Others have also looked into automatically adjusting display colours and contrast to improve their usefulness under bright or changeable ambient lighting [55], particularly for displays in vehicles [9, 50], as well as for mobile displays [29, 60]. However, these studies do not explicitly gather information on what tasks people are typically doing when they experience SVIs, the consequence of SVIs as perceived by the user, and whether any other factors are contributing to the problem.

Poorly designed content may also result in SVIs. Early-career designers typically do not address SVIs and require better support than what is currently available [52]. Reinecke et al. [41] also identified that designers are under-supported when trying to understand a user group's varied perception of colour (influenced by inherited and acquired colour vision deficiency, as well as SVIs). The study quantified the colour differentiation abilities of ~30k web participants in various environments, and found that both increasing ambient brightness and decreasing screen brightness can reduce colour differentiation abilities. However, the effects of ambient and screen brightness were limited because participants were unlikely to put themselves in contexts that increased the difficulty of the study task.

Overall, there is a need to identify the specific causes of SVIs, how people deal with SVIs (or not), and what people's feelings are towards SVIs. As a result, previous solutions that were not informed by the true context of SVIs are potentially inadequate until we fully understand SVIs. In this paper, we use two studies (approved by our university REB) to understand the users, context of use, and adaptation strategies around SVIs, in order to better inform future solutions for SVIs.

STUDY 1: WEB-BASED QUESTIONNAIRE

In our first study, we focused on bright light situational visual impairments (BL-SVI), which we believe to be the most commonly-experienced SVIs. We used an online survey so that we could quickly collect data from a large number of participants worldwide and not limit our findings to one location.

Materials and Procedure

The questionnaire included 11 questions designed to answer our research questions. Q1 and Q2 gathered participant age and gender. Q3-Q5 were used to answer "In what contexts do BL-SVIs occur?". Q6 was used to answer "What are the causes of BL-SVI?". Q7 measured "How frustrating is BL-SVI?" using a rating scale from 1 (Not at all) to 5 (Extremely). Q8-Q10 identified "What strategies are used to overcome BL-SVI?" and Q11 isolated "How often is BL-SVI experienced?".

The questionnaire was distributed to four research groups in other universities, Facebook and Twitter, callforparticipant.com, Reddit.com's r/SampleSize, and xda-developers.com. All questions were optional and visible to participants at once. No remuneration was offered.

Participants

We received 198 responses to our questionnaire, of which 13 responses were removed for reporting on the difficulty of using mobile devices in dark environments (outside this study scope). An additional 11 responses were removed for: missing either 'task' or 'what made completing the task difficult', giving uncorrectable conflicting responses, task difficulty being unrelated to study (e.g., "there were people around"), or providing an overly vague submission or a non-serious reply, leaving 174 responses. Assuming one response per participant, our respondents were aged 18-75 years old (mean=26.88, SD=10.47), comprising 93 males, 79 females, and 2 other.

Analysis of Open-Ended Questions

After reading through each response to become familiar with the data, we analysed it using the following process.

Generating and collating initial codes: The lead author printed and read the responses again, taking note of initial codes. These initial codes were generated using a data-driven approach, then collated and collapsed (e.g., "brightness on screen too low" and "screen brightness on minimum" collapsed to "screen quality and brightness").

Evaluating the suitability of our codes: The first two authors then independently coded 1/3 (randomly-selected) of the responses for each question using the initial codebook, agreeing to identify 'mentions' rather than giving a single code to each response. We then refined our codes and their descriptions by discussing disagreements. We found that participants often misunderstood Q8 ("Were you able to complete your task?") as there was substantial overlap in responses to Q9 ('yes' → "What did you do?") and Q10 ('no' → "What did you do instead?"). For Q9, we expected participants to describe how they overcame their BL-SVI the moment it occurred, but this was not always the case (e.g., P180 responded 'yes' to Q8 but responded "wait until I could go inside" to Q9, so his task was not completed in the moment). We therefore decided to smooth these differences by grouping Q9 and Q10 under a broader question: "What did you do?".

We agreed on the following rules for coding the full data set: 1) count all mentions, 2) if a general response also includes specific examples, count both (e.g., P11: "Play a dark game like Quake or Doom" – "play game", "Quake", and "Doom" were all coded), 3) if a written response includes the word 'and', check to see if this is providing examples (add codes) or an elaboration (no added codes, e.g., P65: "too bright and the brightness was making it difficult to drive", was counted as one mention of brightness).

Coding the full data set: The same authors then independently re-coded all responses with the updated codebook and rules. We could not use Cohen's Kappa to measure inter-rater agreement because we coded the responses more than once (violating the assumption of mutually-exclusive categories [15]), so we opted to use 'percentage agreement' instead. Although this does not factor in agreement that can happen by chance [21], it will be low due to the number of codes available per open-ended question (9-15) and the ability to code multiple times. We first calculated the code agreement percentage per participant response (equal weight). Averaging these, we found high agreement (Q5: 93.2%, Q6: 92.3%. Q9+Q10: 93.6%), and reached consensus by discussing where our coding disagreed.

Defining themes: The first and third authors then reviewed our final coding to identify similarities that allowed thematic grouping. The main themes (described below) provide answers to our research questions for the "causes of BL-SVI" and the "strategies used to overcome BL-SVI".

Results

How often is BL-SVI experienced?

74 participants (42.5%) experienced BL-SVIs once per week, and 28 (16.1%) said BL-SVIs were a problem almost every day, suggesting that BL-SVIs can be a frequent problem in many people's day-to-day lives. 44 participants (25.3%) experienced BL-SVIs once a month, and only 28 (16.1%) reported a BL-SVI frequency of less than once a month.

In what contexts do BL-SVIs occur?

When the BL-SVI occurred, 161 participants (92.5%) reported using a smartphone, 11 (6.3%) a tablet, and one a smartwatch. 166 participants (95.4%) experienced BL-SVI outside and eight (4.6%) experienced BL-SVI while inside.

Our participants experienced BL-SVI while attempting a wide variety of tasks. The three most frequently-reported involved "*text-based communication*" (77 mentions), "*seeking information*" (46 mentions), and "*creating, consuming, or interacting with media*" (39 mentions). There were nine mentions of "*non-specific tasks*", four mentions each for "*checking notifications*", "*enact a system change*" (e.g., unlock device, adjust brightness), and "*making and receiving phone calls*", plus one mention of "*shopping*". Our results support work that showed mobile devices are still mainly used for communication [10].

What are the causes of BL-SVI?

External Influences: There were 123 mentions of causes that related to the environment (e.g., sunlight) and position of device (e.g., the angle the screen is being viewed from). The sun was often blamed for causing BL-SVI (92 times), but there were also 19 mentions of non-sun bright lighting or environment. Eight participants were inside when they had difficulty using their device, so BL-SVI is not exclusively an 'outside+sunlight' problem. Furthermore, 12 mentions related to the direction of light or viewing the device at an angle.

Accessory Interference: BL-SVI can also be caused by interference from human accessories (four mentions, e.g., sunglasses, running armband) and device accessories (one mention). Tinted lenses and screen protectors block light coming from displays, making them appear darker, and running armbands can cause glare by forcing interactions at an odd angle.

Problematic Hardware Design: There were 122 mentions of the physical design of mobile devices (e.g., screen material) increasing BL-SVI severity. Of these, 68 mentions suggested that the display quality (e.g., dark screen, dim backlight) contributes to BL-SVI, and 54 mentions identified glare and reflection. Mobile device screens are typically very smooth glass or plastic, which ensures a sharp display image, but also easily reflects light causing unwanted glare and reflection.

Operating System Inadequacy: Participants identified that their mobile's operating system can increase BL-SVI severity and impede usability. There were 11 mentions indicating that automated adjustments (e.g., auto-brightness, power saving mode) can become a hindrance during BL-SVI. With auto-brightness disabled, the display can be too dark to see during BL-SVI. However, the auto-brightness setting can also be problematic when it is unresponsive, or delayed beyond an acceptable time. In addition, power saving mode can forcibly reduce screen brightness. Automated system adjustments are designed to improve usability by removing the need to manually change settings, however our participants identified instances where this reduced usability instead.

Problematic Interface and Content Design: 39 mentions related to the displayed screen content increasing the severity of BL-SVI. 32 of the mentions indicated it was difficult to perceive screen content (e.g., difficult to read track names). The remaining seven specifically highlight the importance of design (e.g., thickness and colour contrast of icons or text, overall colour scheme). Content displayed on the screen affects BL-SVI and designers need to consider this carefully.

How frustrating is BL-SVI?

This question was asked within the context of Q6, tying the reported level of frustration to a specific task. Figure 1 summarises our results, where 54.0% of our participants rated their frustration at 4 (41.4%) or 5 (12.6%) on a 5-point scale from "Not at all (1)" to "Extremely (5)" frustrating.

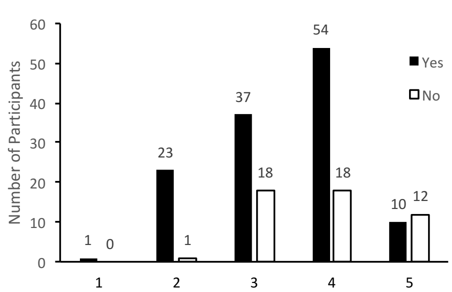

Figure 1. Level of frustration from 1 (Not at all) to 5 (Extremely), split by whether the participant could complete the task or not.

Frustration was significantly lower for participants who completed their task (Mann-Whitney test: $U=2323.50$, $z=-2.62$, $p<.01$), although this had low practical significance ($r=.20$). Furthermore, the median for both groups was 4.0, indicating that regardless of whether our participants completed their task or not, half of each group was still at least very frustrated.

What strategies are used to overcome BL-SVI?

Overall, 125 participants (71.8%) said they could complete their reported tasks and 49 participants (28.2%) could not. P109 selected "yes" but reported two examples – describing both tasks he could and could not complete. P68 could not remember what she did instead when she was unable to complete her task. We identified seven BL-SVI strategies.

Perseverance: Some participants persevered with their tasks (17 mentions), reporting 'pushing through' (e.g., by concentrating more). Five participants mentioned completing the task from memory and four employed squinting. Completing by memory is not without its problems (e.g., the need to "tap a couple of times" (P181) before being successful) and sometimes it is not possible to rely on memory, such as when showing somebody an image. Perseverance does not seem very useful as a general approach.

Change Tactic: It was common for the participants to report relocating as a solution (57 mentions), such as finding shade under a tree. There were three mentions of switching to a different application to complete the task or switching task altogether. Switching location, app, or task is highly inconvenient – there is likely a reason why people are where they are and doing what they are doing.

Fixing Accessories: Some participants described problems caused by accessories. The solution was to remove the device from the accessory or to remove the accessory being worn. It is interesting to note that although one participant (P81) specified the screen protector as part of the problem, it was never removed as part of a solution, possibly due to the inconvenience of later reapplying it.

Adjusting Display: There were 34 mentions of adjusting the display as a (partial) solution to BL-SVI. Thirty-one mentions for increasing screen brightness or contrast (via accessibility options) and three mentions for toggling auto-brightness, or waiting for it to activate. Participants also reported concerns about increased brightness reducing battery life.

Physical Solutions: Our participants reported reducing the amount of light falling on the screen 86 times. There were 61 mentions of shading the device with their body, hand, or an item (e.g., book, clothing). Using a hand or item of clothing to shade the device is not convenient and increases the encumbrance of this solution, especially if the user has no free hand. There were also 25 mentions of reorienting their body and/or device to reduce the light falling on the screen, but this might not always be possible (e.g., a device mounted on a person's arm while running or on the dashboard of a car for GPS).

Waiting: There were 16 mentions of participants waiting until the BL-SVI subsided. If a task is urgent, then delaying it is likely not possible, or could have serious implications.

Not Rely on Device: There were 12 mentions of the participants stopping altogether or closing the application. One participant mentioned relying on someone else (instead of their device). Not being able to use your device to the point of giving up is clearly inconvenient and potentially dangerous.

Limitations

Through this initial web-based survey, we were able to identify many BL-SVI causes and strategies. We recognise that our participant sample was biased in favour of people willing to respond to the survey (potentially over-emphasising severe episodes of BL-SVI). This bias may also have been amplified by having participants recall a past BL-SVI episode. Furthermore, the sample were skewed towards the low end of the age range 18-75 years-old. To address these limitations, we next conducted an Ecological Momentary Assessment (EMA) with a mobile user group balanced by age and gender. We also expanded the focus to all SVIs rather than only BL-SVI so that we could identify differences among types of SVIs.

STUDY 2: ECOLOGICAL MOMENTARY ASSESSMENT

An *Ecological Momentary Assessment* (EMA – a type of experience sampling method [27, 47]) allows us to understand what a person does, feels, and thinks the moment they experience an SVI over the course of two weeks. To help address the memory bias mentioned above, an EMA will allow us to collect a more precise understanding of frequency and frustration as SVIs occur over a fixed period of time.

Following best practice [13, 47], we ran a one-week pilot EMA with six participants. We found that an interval-contingent approach (emailing the participants throughout the day with a short response deadline) was burdensome, while the wording and structure of the self-report needed refining. We made several changes to our procedure and materials as a result.

Participants

We recruited 239 participants by advertising at Australian and Scottish universities, as well as through other online platforms such as those in Study 1. To avoid the self-selection bias identified earlier, we advertised that we were "investigating daily experiences of using a mobile device". Participants only provided age, gender, location, and an email address.

Using this demographic information, we filtered the initial participant list to select twelve participants each from Australia and Scotland. Our study was conducted in February 2018, so participants from Australia were in their summer (brighter environment), and Scottish participants in their winter (darker environment). For each group of twelve, we selected six female and six male participants, and each subcategory of six was selected from different ages (1 from 18-19 years, 2 from 20-29, 2 from 30-39, 1 from 40+) to allow a matching distribution of ages for each subgroup.

We asked these participants to complete an additional demographics questionnaire that included 12 questions. We asked for our participants' age, gender, country and timezone, if they would be visiting another country or timezone during the two-week study, highest attained education, level of computer literacy, if they mainly work or study outside or inside, visual impairments, if they wear contacts or glasses, number of mobile devices they own, make and model of those devices, and typical number of hours a day those devices are used for.

Table 1 summarises the mean age and standard deviation for both gender (male, female) and location (Australia, Scotland). All of our Australian participants were located in the same timezone and all 24 participants indicated they had no plans to visit another country or timezone during the two-week study.

	Male	**Female**	**Australia**	**Scotland**
Mean	30.25	30.67	30.67	30.25
SD	8.50	8.72	8.75	8.47

Table 1. Mean and SD for age (years) by gender and location

The highest level of education attained by the participants was "High School" (3 participants), "College" (1) "Undergraduate University" (10), and "Postgraduate University" (10). Eighteen participants reported "Good" computer literacy, and six reported "Excellent". 22 participants mainly work or study inside, and two participants mainly work or study outside. 14 participants wore glasses or contacts[1]. 11 reported no visual impairments, nine had myopia, one had hyperopia, two had myopia and astigmatism, and one had mild astigmatism.

Our participants' number of mobile devices ranged from one to five (median=2 devices). Nineteen participants owned at least two devices. Typical daily use was between one to 10 hours (median=4 hours); the younger half (18-28 yrs-old) averaged 5.81 hrs and the older half (29-46 yrs-old) averaged 4.14 hrs.

Materials and Procedure

After recruitment, we explained that the purpose of the study was to collect self-reports of SVIs experienced when using a mobile device over a two-week period. We provided participants with an explanation of SVIs that contained information from the Inclusive Microsoft Design Toolkit [36] and the HaptiMap design cards [33], and emphasised that there was no minimum number of SVIs to be reported each day. A link to the SVI explanation sheet was included in correspondence with participants over the duration of the study (details below). Finally, the participants were given an opportunity to ask any further questions via email before the study began.

We used an event-contingent approach [13], in which participants actively recognise SVIs as they happen, and promptly report them when safe to do so. The self-report included nine questions to identify: what device was used, if the participant was inside or outside, where the SVI occurred, what the participant was trying to do, how important the task was, what made it difficult, how frustrated the participant was, what strategy/ies were used (if any) to overcome the SVI, plus any additional comments. Each morning at ~0700 (local time), participants received an email reminder about the study that included links to the self-report and the SVI explanation page.

An end-of-day report was emailed every evening at ~2045 to check that our participants were still in that same timezone, if any SVIs experienced that day were not reported, how many were not reported, and why the SVI was not reported at the time it occurred. If there were any missed self-reports, then the participant was asked to describe one of the unreported SVIs. We required that participants submit an end-of-day report every evening so we could check who was still engaged with the study because a participant may not experience an SVI every day and therefore may not submit any self-reports.

[1] P19 wore glasses to correct a lazy eye rather than for visual acuity.

After the two-week period, the participants were sent a final questionnaire. All participants (except P16) were asked four main questions to identify: 1) if their mobile device use was typical, 2) if their engagement was consistent, 3) what was the cause for frustration when experiencing SVIs, and 4) any additional comments. Due to not experiencing any SVIs, P16 received the first two questions and was asked if he had experienced SVIs outside of the study period. We also asked 12 participants questions about their experience with auto-brightness, seven participants for additional information about their reported SVIs, six participants for clarification of the time a report was submitted, and two participants if an issue they were reporting had occurred before. Any further discussions to clarify responses were carried out over email. We reimbursed participants with a £20 or AU$36 voucher.

Results

Twenty-two of our participants indicated that their mobile device usage was typical for both weeks of the study. P16 indicated that due to illness, his usage was higher over three days on account of not being able to use a computer.

Eighteen participants indicated that they felt their engagement was consistent during the two-week study (P17 answered so but said there may have been a decrease over three days due to university commitments). Five participants said that their engagement changed. P2 said that during the last 3-4 days of the study, his responses were not as quick as before, but would still report within half an hour. P8's engagement decreased during the beginning of week 2. P13's engagement decreased during the end of the study. P16's engagement was lower during the week since he was less likely to use a mobile device while working. P16 increased his phone use over three days when he was away from work. P24 indicated decreased engagement during week 2 due to work commitments.

P16 was the only participant not to report any SVIs. When he was asked if he had experienced any SVIs outside of the two week study, he was able to recall past events where the sun caused an SVI and he would have to manually increase brightness. P16 also said "Given the time of year and the weather, I haven't spent much time outside so [the sun has not] been an issue." This variability was clear in the data, and not unexpected considering the different seasons of Australia and Scotland, which is something we wanted to observe.

We removed 15 out of 423 submitted reports. Seven reports (three self-reports and four end-of-day reports) were removed because the reports were not SVIs and eight end-of-day reports were removed because they were extra submissions. Out of the remaining 408 reports there were 88 self-reports and 29 end-of-day reports describing an SVI event.

Adjusting for any late report, Figure 2 shows the heatmap distribution of SVIs experienced by the participants. Two participants indicated that they missed reporting two SVI events, although the end-of-day report allowed them to provide details about one of those events. On day seven, data gathering for the Australian participants was limited to only end-of-day reports due to a technical disruption. As expected with an involved methodology [47], there was a decrease in engagement over two weeks, however, we know from the submitted end-of-day reports that the participants were still engaging with the study.

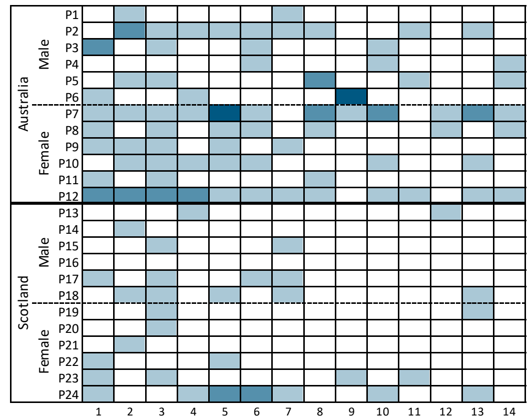

Figure 2. The total number of SVI events per day across 14 days. White squares indicate 0 and blue, getting darker, indicates 1 to 3 SVI events.

A similar approach to Study 1 was used to analyse the open-ended questions. The lead author became familiar with the data. Next, the Study 1 codebook was used by the lead author to code the data and adjustments were made to the codebook to reflect the broader scope of the new data set (e.g., we did not remove bright screen in dark room SVIs). Finally, the first two authors independently coded the full data set and did not count mentions that were only providing additional contextual information. We found high agreement for all questions: "Where did this SVI experience take place?" 91.03%, "What were you trying to do?" 93.85%, "What made it difficult?" 81.12%, and "What strategy (or strategies) did you use to overcome the SVI?" 88.58%. Disagreements were discussed and re-coded, and the codebook was refined to address the disagreements.

In what contexts do SVIs occur?

Overall, there were a total of 67 reported SVIs that happened inside (50 for the Australian group and 17 for the Scottish group) and 50 reported SVIs that happened outside (34 for the Australian group and 16 for the Scottish group). There are many different places the SVI event took place: home (36 mentions), in a public space (28 mentions), transport (27 mentions), work or school (23 mentions), while being active (10 mentions), in a shop (three mentions), at an event (one mention), and at the hospital (one mention). We were unable to categorise two responses.

Similar to Study 1, our participants experienced SVIs during many different tasks, including: "*seeking information*" (47 mentions), "*text-based communication*" (33 mentions), "*creating, consuming, or interacting with media*" (19 mentions), "*navigation and maps*" (eight mentions), "*shopping and payments*" (seven mentions), "*checking notifications*" (seven mentions),"*enact a system change*" (three mentions), "*setting up device or application*" (three mentions), and "*making and receiving phone calls*" (one mention). There were two "*non-specific*" responses. The top three tasks are the same as in Study 1. Setting up device or application was a new code and the previous code for shopping was expanded to include mentions of payments with the device.

What caused the SVI event?

In Study 1, we identified five themes for causes of BL-SVI. For Study 2, our data for different types of SVIs continues to support the validity of those themes. However, it was clear that we needed to consider more deeply the individual within their context, similar to previous research [48]. Our themes for Study 2 are: “External Influences”, “Accessory Interference”, “Problematic Hardware Design”, “Operating System and Software Inadequacy”, “Problematic Interface and Content Design”, and “Cognitive and Physiological Effects”.

External Influences: There were 98 mentions of causes that related to the environment. Similar to Study 1, the sun made up the majority of mentions (34). However, since Study 2 broadened our interest to all types of SVIs, we received responses that were more varied. There were 24 mentions of dark environments, 18 mentions of viewing angle, 17 mentions of bright environments, three mentions of moving environment (e.g., P7: “The bus kept shaking (more than usual) so it was hard to see the screen.”), and two mentions of physical obstacles (e.g., dirt on the display of the device). Not surprisingly, there were over twice as many mentions of the sun (24) and bright environment (14) in the Australian group, compared to the Scottish group (10 and 4, respectively).

Accessory Interference: There were 9 mentions related to human and device accessories. Eight mentions were accessories used by the participants (P2: “I didn’t have my glasses so reading was more of a strain than normal.”) and one mention of a screen protector making “...the screen unclear..." (P10).

Problematic Hardware Design: There were 85 mentions of the physical design of the mobile devices to cause or exacerbate SVI events. Similar to Study 1, 61 mentions suggested that the quality of the display technology is a factor, however, in this case these were not all examples of BL-SVI. Some of the SVIs experienced in a dark environment were due to the screen being too bright. It is also possible that in a dark environment the display can still be too dim to view the content (P12: “The tablet brightness was low and the lights in the room were also dim making it hard to see the text on the screen.”). Glare and reflections were mentioned 24 times.

Operating System and Software Inadequacy: Data from Study 2 provided us with new information that required us to expand this theme to summarise 27 mentions of general software issues that could be either operating system level problems or application specific. Similar to Study 1, there were 10 mentions indicating that automated adjustments (e.g., auto-brightness, power saving mode) can factor into SVI events.

There were 15 mentions about using a blue-light screen filter, which are typically used to reduce blue light for better nighttime viewing and improved sleep [12]. None of the 13 submissions removed from Study 1 for discussing SVIs in a dark environment mentioned the use of a blue-light filter. Blue-light filters can cause a variety of problems (P2: “The night-light blue filter made my phone screen too dark, making it difficult to use”, P3: “Trying to play [a game] where you have to match colored dots. [The blue-light filter] made some colours impossible to distinguish”, and P21: “I had the brightness on my phone turned down with a screen filter (blue light) applied, from using my phone in bed the night before. I tried to use my phone in the living room and the overhead light was too bright combined with the low brightness of the phone screen.”).

Finally, there were two mentions of apps causing SVI events. The first is an example of the app taking control of system settings, P10: “The app makes brightness 100% immediately which was too bright, especially on a Monday morning” and the second example was an app not rotating which resulted in the content missing from a website.

Problematic Interface and Content Design: Seventy-six mentions related to the content displayed on a mobile device or the difficulty of seeing what was on the display. Fifty-one of the mentions indicated it was difficult to perceive screen content, whereas there were 25 mentions that provided informative details about aspects of the interface layout or content design that related to the SVI event. Use of colour and colour contrast is important. A challenge is predicting when high-contrast is required (P8: “I was reading a website and their background was black and their text was grey. I had troubles reading the content”) and low-contrast is required (P24: “The contrasting colours chosen by the bank were very bright.”). Text size is also important, as is how an interface is rendered in a different orientation (P18: “...In portrait mode the site I was browsing had missing options at the top of the page and at the side of the page.”). Furthermore, content that overlays other content on the screen was also problematic (P5: “The content was not well formatted for a mobile screen and an ad kept overlaying the content as well.”, P8: “I was trying to make a phone call but [Facebook Messenger] notifications kept popping up making it hard to make the call.”). Applications can also enable people to adjust colour settings, but this can have unexpected consequences (P7: “This one email had multiple sales for different brands but since I set the background to black, the logos had no contrast.”).

Cognitive and Physiological Effects: Finally there were a total of 19 mentions that did not fit within our previous themes. There were 11 mentions regarding discomfort and pain as a result of the context (P2: “I didn’t have my glasses so reading was more of a strain than normal”, P17: “Dark outside, the screen was too bright to look at comfortably”) and there were eight mentions of SVI events due to recently waking up (P3: “Screen brightness was way too bright after waking up, usual phone wallpaper is dark but once in the email app [it] has a white background”, P5: “After having had my eyes closed, they were slow to adjust to the brightness of my screen”).

What strategy (or strategies) are used to overcome SVIs?

There were 76 reports demonstrating a single strategy was used or considered to overcome the SVI event (P14: “Turned up screen brightness”) and 32 reports demonstrating more than one strategy was used or considered to overcome the SVI event (P2: “I increased the screen brightness and adjusted the angle of my tablet, but still had some problems with the glare and brightness”). Four reports highlighted an unsuccessful or unused strategy. If an SVI can be addressed with different strategies, then one unsuccessful attempt may result in another strategy being employed (P7: “I told her to turn the lights off but she didn’t so I turned up my brightness.”).

There were 14 reports in which participants were unable to overcome the SVI (P9: “I couldn’t really do anything as I was walking outside without shade.”), even after attempting to address the problem (P7: “I couldn’t turn my brightness up because of the low battery so I gave up.).

Overall, the seven themes identified in Study 1 were sufficient to summarise new data on how people deal with SVIs.

Perseverance: There were a total of 23 mentions. Similar to Study 1, we found evidence of continuing on (three mentions) and completing by memory (two mentions). In the previous study, our participants mentioned squinting (likely to be more common in bright environments). With Study 2, we found 18 mentions of squinting and other perceptual strategies utilised by the participants (P7: “I had to stop looking at my phone and close my eyes.”, P17: “Waited for eyes to adjust.”).

Change Tactic: We found 24 mentions that could be summarised as the participant changing tactic. As with Study 1, our participants in Study 2 would also relocate (nine mentions) and switch their approach (four mentions). However, new findings in Study 2 showed that participants would use alternative app features (eight mentions; P1: “Listen to gps voice instead of looking at it”), charge the device (two mentions), and reboot the device (one mention).

Fixing Accessories: Similar to Study 1, when we asked the participants what was contributing to the SVI event, both human and device accessories were mentioned. It is interesting that we received three mentions of solutions about removing the human accessory (P10: “Change to standard glasses (not prescription sunnies I was wearing).”) and there was no evidence of addressing the device accessory cause of the SVI. This reinforces our belief that the solution of altering the device accessory is too inconvenient.

Adjusting Display: There were 52 mentions regarding adjustments to the display. We found seven mentions of auto-brightness and 32 mentions of manually adjusting the display to resolve the SVI. We also found 13 mentions where a screen filter was adjusted because it was causing the SVI (P12: “I paused the blue light filter on my phone.”).

We asked 12 participants follow-on questions about their experience with auto-brightness based on patterns of behaviour demonstrated in submitted reports. Seven participants found auto-brightness to not be effective (e.g., it makes the display too dim or too bright), three participants turned it off to save power, while one participant was unaware of the feature prior to the study and one participant likely turned it off by mistake because he typically keeps it on.

Physical Solutions: There were 23 mentions of physical solutions. Similar to Study 1, we found evidence of creating or using local shade (nine mentions), as well as reorienting the body and/or the device (37 mentions). We found two new approaches: removing an obstacle (one mention; P18: “...used my thumb to flick the paper off.”) and adjusting the room lighting (five mentions; P3: “Manually reduced brightness, and turned on bedside lamp to reduce contrast”, P7: “I finally got out of bed, turned off the light, opened the blinds, and resumed using my phone at my desk instead.”)

Waiting: We found nine mentions of waiting for the problem to subside (P13: “Waited until I was inside.”), but this is not always an option, especially for important tasks.

Not Rely on Device: We counted 10 mentions that suggested the user could not overcome the SVI when using the device. There were also two mentions of speaking to somebody as a method to overcome the SVI (P24: “I mentioned to a friend who showed me the brightness setting on my phone.”).

Task Importance & Frustration

We included a question in Study 2 to measure task importance because Study 1 highlighted that tasks completed on mobile devices range in importance for several reasons. Mobile devices are used to stay connected, for entertainment, and to keep on top of work and school-related tasks.

We ran a Spearman’s correlation on the ratings for task importance and frustration using only the self-reports that were submitted after an SVI event (N = 79). By excluding late self-reports and the end-of-day reports, we minimise any influence that elapsed time may have on the reported task importance and frustration with the SVI. Based on the results of the analysis, we found that as task importance increases so does the amount of frustration experienced during the SVI event (r_s = .49, $p < .001$), which confirms our expectations from Study 1.

Our participants provided several reasons for feeling frustrated: inconvenience by disrupted activities (mentioned by 12 participants), resulting discomfort (mentioned by four participants), experiencing a lack of control (mentioned by eight participants), annoyance (mentioned by two participants), and when the task is important (mentioned by one participant). P24 said “my lack of IT knowledge” referring to not knowing how to resolve SVIs (e.g., adjusting the screen brightness). Five participants mentioned that they were usually not frustrated by SVIs (e.g., due to their typically brief duration).

DISCUSSION

We found five main results:

1. SVIs were frequently experienced in both studies.
2. SVIs occur during many different tasks.
3. Factors causing SVIs are: environmental (e.g., lighting, moving surroundings, physical obstacles), device position, human and device accessories, hardware design, software and system settings, content design, and cognitive and physiological effects. Simultaneous factors exacerbate SVIs.
4. SVI frustration has a statistically significant positive correlation with task importance.
5. Many strategies are employed to overcome SVIs, with evidence of combining strategies for more severe SVIs. However, combined strategies do not always eliminate SVIs.

We found not all SVIs are created equal, echoing previous research [44]. In general, situational impairments are very complex due to the number of variables that can factor into experiencing the phenomenon. Finding solutions for SVIs is not a simple task and based on our data, different stakeholders need to work together towards mitigating SVIs.

We live in a world that is always connected and disruptions when using mobile devices are usually unwelcome. Although some SVIs are no more than a mild inconvenience and are unlikely to cause any significant problems for mobile device users, we must recognise that people rely on being connected for many different reasons (e.g., as part of their job, to stay connected to distant family members). While mobile device users can cope with SVIs during less important tasks, levels of SVI frustration increase as the task trying to be completed becomes more important. The wide range of SVIs that can occur makes it very challenging to eliminate all SVIs, particularly when many factors are involved, and sometimes waiting is the safest solution. However, there are still causes of SVIs that can be addressed. We outline several design implications and solutions, as well as a new mobile device SVI context model.

Implications for Design

The findings of both studies demonstrate that mobile device SVIs are a complex problem. It is evident that a single solution will not address SVIs because they are not caused by any single factor and there can be many contributing factors at one time.

Accessory Interference: We found that human and device accessories can create problems for mobile interaction and there is potential for novel ways of designing accessories to minimise SVIs from occurring. For example, sunglasses were identified as a contributor to SVIs in bright environments – the tinted lenses make a mobile display appear darker and if lenses are polarised then it can further darken the mobile screen. One solution could be 'digital sunglasses' that track the location of the mobile device and overlay a clear "window" that lines up with the device's screen, while maintaining a darkened view for anything that is not the device's screen. Using this approach, a person will not need to remove their sunglasses. Workers in hazardous environments required to wear dark or coloured goggles would also benefit from a digital solution.

Problematic Hardware Design: The design of mobile device hardware needs to be carefully considered in order to minimise the occurrence of SVIs. Reflections and glare were frequent problems experienced by our participants. Manufacturers could introduce the option of having a matte display to reduce reflections and glare, but this could introduce some image degradation [8, 39]. Increasing maximum screen brightness is also impractical due to the effects it would have on battery life and it is likely to increase the cost of mobile devices. An alternative approach would be moving the mobile industry towards using transflective displays [5], which retain good readability in both bright and dark environments.

Battery life can contribute to SVIs. Our participants reported that they would reduce screen brightness to conserve power. Outwith the user's control, mobile devices employ 'power saving mode' that reduces screen brightness automatically. Fast charging solutions are no help when a power source is unavailable (e.g., when outside). A design consideration that could be made is to allow important parts of the display to remain brighter (e.g., the mobile status bar for notifications), even during power saving mode, although this would be better with OLED displays where each pixel has independent brightness.

Operating System and Software Inadequacy: Automated settings are intended to save the user from having to make changes to system settings manually. However, our participants identified how these can contribute to SVIs.

Auto-brightness could be slow to adjust the screen brightness, or it would settle on a brightness level that was not satisfactory. Previous work has identified issues with the accuracy of adaptive brightness models and has developed new approaches to calculating the appropriate brightness level [32, 46]. Sometimes auto-brightness is turned off and the user is forced to attempt to increase the screen brightness manually. A solution to explore would be providing auto-brightness permission to turn itself on if certain thresholds are met. Alternatively, similar to Trewin's automating accessibility work [53], if the display brightness is low, then a user's mistyping or inaccurate target selection could be used to inform the system that more light might be required so the user can see what they are doing.

Finally, the Operating System (OS) could help address SVIs caused by power saving mode. One solution would be to allow customisation of what this setting can control, e.g., the user gives power saving mode permission to restrict CPU power but not permission to limit the screen brightness.

On the other hand, we could make use of OS and software level features to help reduce SVIs. Both of our studies highlight the complexity of SVIs with regards to time. It became apparent from our participants' reports that the sequence of previous events can lead up to an SVI occurring (e.g., your battery runs low while you are inside playing a game under low ambient lighting. Later, you step outside with auto-brightness turned off and it is difficult to see content on the display. You are able to increase the brightness from memory, but the phone has entered power saving mode, thus capping the maximum brightness). Mobile devices these days have built in AI assistants, which could be used to warn users about how current usage may affect future mobile interaction.

Problematic Interface and Content Design: Creating solutions for improving mobile content design is perhaps the most practical first step towards addressing SVIs because designers have control over the look and functionality of their content. Research has demonstrated that data highlighting interaction issues can be used to inform the exploration of novel interface designs that would overcome previous limitations [17].

Some SVIs occur in such a way that a person no longer has control (e.g., when caused by content design). In Study 2, when we asked why SVIs are frustrating, three participants discussed content design; P8 said her frustration with design was a factor because she could not control the design, P18 had a lower opinion of organisations whose designs factored into experiencing an SVI, and P22 recommended website designers should consider and plan for SVIs.

One challenge with SVIs is predicting when high-contrast for bright environments and low-contrast for dark environments is required. There is research that has investigated ways to automatically recolour the display for enhanced viewing in bright and dark environments [60]. Automatic recolouring is convenient but can add to battery depletion due to increased sensor monitoring, while simultaneously altering the designer's artistic intent. It is worth pursuing how to provide users with active control in recolouring a display and supporting designers in being able to add this functionality into mobile app interfaces.

Early-career designers feel that current support for designing to reduce SVIs is lacking and they want improved guidelines, education, and digital design tools [52]. Although accessibility guidelines impose restrictions on design, it is possible to maximise creative freedom with a design tool [51]. Using our data, we plan to run several design workshops with mobile app interface designers. The goal of the design workshops will be to co-design a new design tool and testing protocol that provides designers with support in reducing SVIs (e.g., by rapidly generating alternative colour schemes that improve viewing in very bright or very dark environments). Furthermore, mobile devices are starting to adopt high dynamic range (HDR) displays, which extend the range of colours and contrast compared to typical displays [2]. Designers can take advantage of HDR's wider range of colours and higher brightness levels to maximise success for context-specific interface colour modes.

Mobile device SVI Context Model

Sears et al. [48] and Vatavu [54] previously introduced diagrammatic representations considering situational impairments, however the first model did not focus on mobile devices and the second extended beyond SVIs to look at all factors affecting visual perception. To address these limitations, we introduce a mobile device SVI Context Model (Figure 3) influenced by our novel and relevant empirical data.

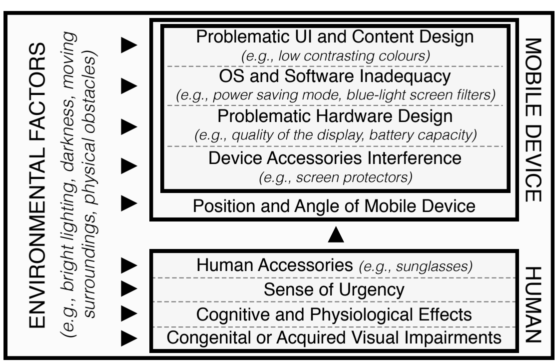

Figure 3. Our mobile device SVI Context Model considering the layers between the user and the content, all under environmental factors.

The ever-changing environment has a continual influence on user interaction. The previous models do not explicitly show the omnipresence of the environment. We situate the human and mobile device within the environment and using arrows we emphasise the environment's influence at each level.

Similar to the previous models, we recognise that humans have their own physical, perceptual, and cognitive limits when interacting with devices. However, we also emphasise the user perception of urgency towards completing the task, which can also be affected by environmental factors. The value of reducing the effects of SVIs increases when the task becomes more important. Furthermore, the user may wear accessories to counter environmental conditions or for improving activity performance, and these can introduce or increase SVIs.

Our model is unique in emphasising SVIs imposed by human and device accessories. We replace Sears et al's Applications dimension with a four-level representation of the mobile device, indicating each level that could introduce or increase SVIs. Position of device is also indicated as this was a factor in SVIs. In some cases, the participants could reorient themselves or the device to change how light fell on the screen, however, this is not always possible if the device is in a fixed position (e.g., placed in an armband or on a car dashboard hands-free mount). First, we highlight the "device accessories" level; people will personalise their devices [35], yet protective cases and screen covers can alter user interactions and increase the reflectivity of the display. The next level is "hardware", which involves the physical device and its components, e.g., the maximum brightness of a low-cost tablet could be insufficient, thus having an adverse effect on the user when viewing the screen in direct sunlight. Next the "OS and Software" can introduce or increase SVIs through automated mechanisms (e.g., turning on power saving mode or the blue-light filter). The final level is the "content" being consumed. The on-screen content can introduce or increase SVIs if it is poorly designed (e.g., low-contrast between the text and background).

Our model visually represents the findings of our two studies to provide different stakeholders (e.g., HCI researchers, engineers, manufacturers, designers) with a concise overview of the complex nature of SVIs. Our model is especially useful for people who are studying and who are unfamiliar with SVIs.

LIMITATIONS AND OTHER FUTURE WORK

Mobile devices are finding their way into high-risk occupations, yet our study focused on the general population, without deliberately seeking participants in those professions. We have assessed the "typical" SVIs experienced by regular mobile users, but future work should target other user groups (e.g., people using safety-critical systems) to broaden our findings.

Sarsenbayeva et al. [43] have identified other (non-visual) situational impairments that require further research. We recommend our EMA approach to gain a deep and ecologically valid understanding of other situational impairments.

CONCLUSION

We recruited 174 participants for an online survey and 24 participants across Australia and Scotland for a two-week ecological momentary assessment to establish what factors contribute to mobile device situational visual impairments (SVIs). Our analysis reveals SVIs are a complex phenomenon with several contributing and interesting factors. Multiple solutions will be required to reduce SVIs. We propose preliminary solutions to SVIs and present a mobile device SVI Context Model that highlights the identified problem space for the benefit of HCI researchers when creating mobile SVI solutions.

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